ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB386

DESIGN STUDY OF THE Nb_3Sn COS-θ DIPOLE MODEL FOR FCC-hh

R. U. Valente*, S. Mariotto, M. Prioli, E. De Matteis, M. Statera, M. Sorbi[1]
Istituto Nazionale di Fisica Nucleare sezione di Milano, Milano, Italy
S. Burioli[2], P. Fabbricatore, S. Farinon, F. Levi[2], R. Musenich, A. Pampaloni
Istituto Nazionale di Fisica Nucleare Sezione di Genova, Genova, Italy
D. Tommasini, F. Lackner, CERN, Geneva, Switzerland
[1]also at Università degli Studi di Milano, Milano, Italy
[2]also at Università degli Studi di Genova, Genova, Italy

Abstract

In the context of the Future Circular Collider hadron-hadron (FCC-hh) R&D program, the Italian Institute of Nuclear Physics (INFN), in collaboration with CERN, is responsible for designing and constructing the Falcon Dipole (Future Accelerator post-LHC Costheta Optimized Nb_3Sn Dipole), which is an important step towards the construction of High Field Nb_3Sn magnets for a post LHC collider.

The magnet is a short model with one aperture of 50 mm and the target bore field is 12 T (14 T 'ultimate' field). The dipole is pre-loaded with the Bladder&Key technique to minimize the stress on the coils at room temperature, which are prone to degradation because of the Nb_3Sn cable strain-sensitivity.

The electro-mechanical 2D design is focused on the performance, the field quality and the quench protection, with emphasis to the stresses on the the conductor. The Falcon Dipole has been modelled in a 3D FEM to determine the peak field distribution and the influence of the coil ends on the field quality.

INTRODUCTION

The main goal of the Falcon Dipole is to develop a significant model in the range of 12-14 T to consolidate the state-of-art for Nb_3Sn accelerator dipole with a robust design suitable to the industrial production, achieving an important technology milestone for high accelerator magnets, as intended by the next generation colliders [1–6].

In this paper we present the final design of the magnet, which is the result of a compromise between performance and technical feasibility. The main critical aspect is the strain sensitivity of the Nb_3Sn cable, indeed, on the basis of the experience from magnet tested in the past, the stress inside the coils should be lower than 150-200 MPa [7] in order to avoid permanent degradation of the conductor. For this reason, we adopted stringent requirements for the structure of the Falcon Dipole, e.g. the minimum bending radius of the cable >10 mm, the minimum copper wedge thickness >1 mm and a smooth inter-layer transition in a comfortable position.

ELECTROMAGNETIC DESIGN

The minimum target is to achieve a bore field of 12 T when the magnet is cooled at 1.9 K, but in principle the design allows to reach a 'ultimate' field of 14 T. The wire used to produce the cable is an existing conductor provided by CERN as in-kind contribution, which is a RRP Nb_3Sn Ti-doped wire of 1 mm diameter with a filament size of 58 µm. A preliminary measurement, made on short-samples by the manufacturer, reported a minimum critical current density value of 1267 A mm^{-2} and an average value of 1341 A mm^{-2} [8]. The INFN team is planning in 2021 a measurement campaign to characterize the conductor, in order to confirm those results and to understand the heat treatment consequences in terms of performance and deformations.

The coils will be winded following the cos-theta layout with a keystoned Rutherford cable of 40 strands of the conductor mentioned above. In the design, the expansion due to the heat treatment is taken into account, i.e. width +2% and mid-thickness +4.5%, neglecting the longitudinal dimension variation. In addiction, the cable is equipped with a Stainless Steel (SS) foil core to reduce the inter-strand coupling losses (ISCC) and to reinforce mechanically the cable. The expected values both of the wire and the cable are summarized in Table 1.

Table 1: Strand and Cable Expected Parameters

Wire Parameter	**Value**
Superconductor	Nb_3Sn
Strand diameter [mm]	1.0
Cu/non-Cu	0.9 ± 0.2
I_c at 4.22 K, 16 T [A]	560 ± 14
Filament diameter [µm]	58
Filament twist pitch [mm]	19 ± 3
RRR, rolled	159 ± 14
Heat treatment temperature [°C]	665
Cable Parameter	**Value**
Number of strand	40 (2 × 20)
Keystone angle [°]	0.5
Glass insulation thickness [mm]	0.15
Strand twist pitch [mm]	120
Width (unreacted/reacted) [mm]	21.00 / 21.42
Thin edge (unreacted/reacted) [mm]	1.72 / 1.80
Mid-thick (unreacted/reacted) [mm]	1.81 / 1.89
Thick edge (unreacted/reacted) [mm]	1.90 / 1.99
Packing factor	74.7%
Overall deformation	86.8%

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* riccardo.valente@mi.infn.it

The dipole has one aperture of 50 mm and two layers winded with the 'pancake' technique. The nominal current is 20930 A (bore field 12 T), the ultimate current is 24838 A (bore field 12 T) and the theoretical short sample current is 27999 (bore field 15.6 T). The Falcon Dipole is modelled in ROXIE software [9] and the load line is constructed starting from the Bordini fit for the Nb_3Sn critical current density, which depends on the magnetic field and the temperature. The margins on the load line, reported in Fig. 1, are computed considering the peak field on conductor, which is located in the pole turn of the block 3 as indicated in Fig. 2. Other parameters related to the magnet performance are reported in Table 2.

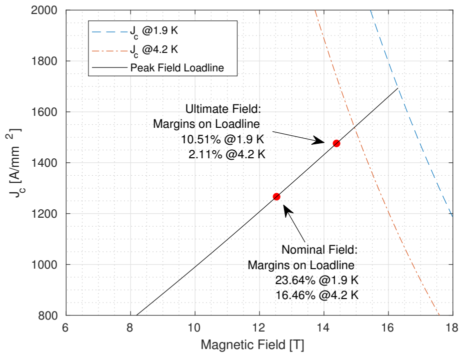

Figure 1: Loadline of the Falcon Dipole and margins at 4.2 K and 1.9 K.

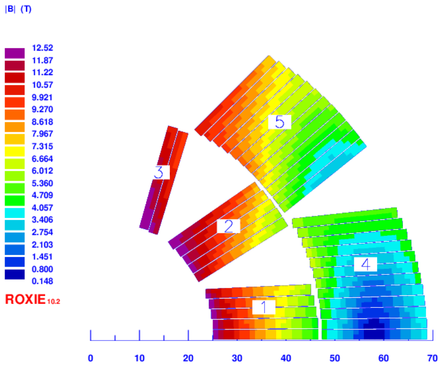

Figure 2: Field map of one quadrant of the coil cross section at 20930 A, i.e. a bore field of 12 T.

The field quality analysis is performed with ROXIE, assuming the 2D series expansion of the magnetic field at the reference radius of 16.667 mm. The results of the computation are reported in Table 3, in particular the normalized allowed harmonics b_n (expressed in 'units', i.e. 10^{-4} times the reference field) due to the winding geometry and the saturation (geo+sat), but also when the persistent current effect (pc) is included. The magnet construction feasibility is the most priority of the project, therefore the requirement on harmonics is not stringent as for typical accelerator magnets, but still some solution has been studied and in principle it is possible to improve the field quality successfully [10].

Table 2: Magnet Parameters Evaluated With ROXIE

Bore Field [T]	**12**	**14**
Current [A]	20930	24838
Overall Current Density [A mm^{-2}]	440.17	522.35
Peak Field [T]	12.53	14.39
Short Sample Current [A]	27999	27999
Operational Temperature [K]	1.9	1.9
Margin on Loadline [%]	23.64	10.51
Temperature Margin [K]	5.12	2.73
Enthalpy Margin Cable [mJ cm^{-3}]	230.96	157.17
Stored Energy [MJ m^{-1}]	0.544	0.741
Diff. Self-Inductance [mH m^{-1}]	2.250	2.187

Table 3: 2D Field Quality Parameters

Parameter	**Value**
Reference Field [T]	12
Reference Radius [mm]	16.667
Transfer Function (geometric) [T kA^{-1}]	6.029×10^{-4}
Transfer Function (saturation) [units]	-489.1
Harmonics [units]	**geo+sat/pc**
b_3	-0.01 / 0.23
b_5	-5.30 / -5.44
b_7	12.59 / 12.81
b_9	2.84 / 2.89

Another critical aspect of the Falcon Dipole is the coil ends design, in particular the pole turn and the layer jump, because that's where the risk to damage the cable is higher. The 3D electromagnetic model is implemented in ROXIE and the coil ends are designed minimizing the strain in the cable using a differential geometry optimizer tool (Fig. 3). The end-spacers are designed to keep the peak field in the coil ends and along the jump layer lower than in the straight part, but also to maintain the integrated harmonics close to zero (see Table 4).

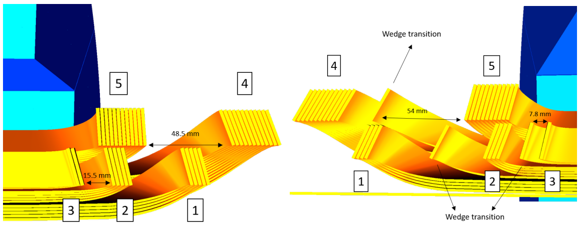

Figure 3: Coil ends longitudinal section: on the left the return ends and on the right the exit ends.

MECHANICAL DESIGN

The mechanical structure of the magnet is based on the Bladder&Key technique, in order to keep the stress on the coils during the assembly, the cool down and the powering of the magnet, under the threshold of 150 MPa [11],

Table 4: Electromagnetic 3D Model Parameters

Parameter	**Value**
Coil Length (end-to-end) [mm]	1500
Magnetic Length [mm]	1336.4
Iron Yoke Length [mm]	1200
Peak Field on Straight Part [T]	12.70
Peak Field on Return Ends [T]	12.45
Peak Field on Exit Ends [T]	12.33
Normal Integrated Harmonic	**Units**
$\bar{b}_3$	18.21
$\bar{b}_5$	-5.17
$\bar{b}_7$	12.01
$\bar{b}_9$	2.85
$\bar{a}_1$	20.04
$\bar{a}_{n>1}$	<|1|

which is the empirical limit before the critical current of the Nb_3Sn cable is subjected to permanent degradation. More precisely, part of the pre-stress on the magnet structure is given at room temperature using calibrated interference keys inserted by means of water-pressurized bladders, and the rest of the pre-stress is given during the cool down taking advantage from the different thermal contraction between an outer Alumimun shell and the inner components of the structure (Fig. 4).

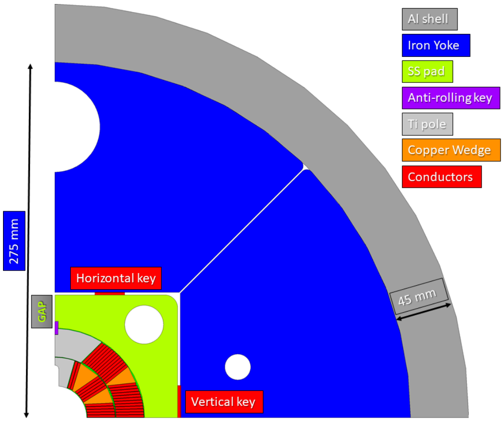

Figure 4: Cold mass structure.

The mechanical optimization, performed with ANSYS [12], allows to keep the stresses on each magnet component below the yield strength limit and ensure that the coils are never in traction, which means positive contact pressure between the winding and the titanium pole. The FEM analysis methodology is described in detail in past works [13–15], here we present the results of the Von Mises stress computation on the conductor (Fig. 5), which is obtained using a horizontal key 0.15 mm thick and the vertical one of 0.35 mm. In principle, to power the magnet at the ultimate field of 14 T, the vertical key thickness has to be set 0.55 mm thick, obtaining a peak stress of 140 MPa.

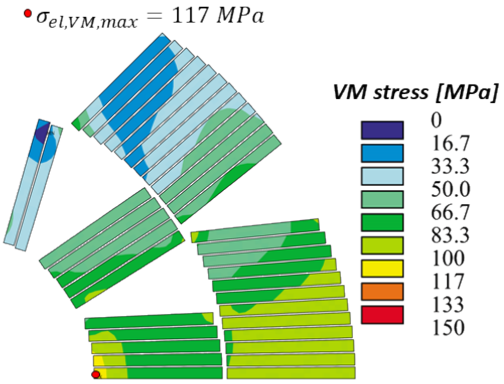

Figure 5: Von Mises stress on coils computed over the elements, when the magnet is powered at 12 T nominal field, after the assembly and cool-down.

QUENCH PROTECTION

The quench protection analysis has been performed with LEDET [16] and validated with QLASA [17]. The most conservative scenario is considered, that is the quench starts where the peak field is located and propagates in the transverse direction, between adjacent turns and layers. Since the magnet is short (1.5 m long), the protection scheme chosen is the energy extraction system that allows to extract large part of the Joule energy in a dump resistor and to discharge safely the magnet, limiting the temperature increase below the 350 K threshold. The dipole is easily protected with a dump resistor of 25 mΩ, assuming an activation time of 30 ms, i.e. 8 ms of detection, 20 ms for the validation (ohmic voltage threshold 100 mV) and 2 ms to trigger a solid-state switch. The hot-spot temperature reached is 160 K and 235 K at nominal and ultimate field respectively, and the voltage to ground is always below 625 V.

CONCLUSION

The electromagnetic design presented allows to achieve safely a bore field of 12-14 T, thanks to geometrical constraints imposed to ensure the technical feasibility. From the point of view of the mechanics, the results suggest the Bladder&Key solution is suitable for the Falcon Dipole even at the ultimate field. As expected, the quench protection is not a critical aspect, therefore the energy extraction system is sufficient to discharge safely the magnet in case of quench.

A large number of coils is planned to be fabricated in the industry in the next years and in parallel a measurement campaign to characterize the conductor is starting. Moreover, mock-up tests on the structure are planned to check mechanical tolerances and validate the FEM computations.

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